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COHERENT OPTICAL CORRELATION IN REAL TIME FOR MISSILE TERMINAL --ETC(U)
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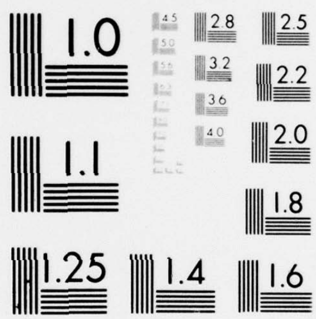

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*CHRISTENSEN, UPATNIEKS and GUENTHER

(6) COHERENT OPTICAL CORRELATION IN REAL TIME FOR MISSILE TERMINAL GUIDANCE, (U)

JUN 1978

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INTRODUCTION

The use of area correlation in terminal guidance requires that the system cross correlate a stored reference with the observed scene and have the capacity for handling variations in aspect angle, rotation, scale and intensity. This correlation must be made in real time at a low false alarm rate.

Digital techniques can accomplish the preceding requirements but have several limiting characteristics. The number of resolution elements that can be processed is limited by the available core memory. Even with well-chosen algorithms, a large number of multiplications and additions are required and these increase with the number of resolution elements. For the hypothetical situation of cross-correlation of a reference pattern having 100 X 100 resolution elements against a scene with 200 X 200 elements, 10^4 multiplications and additions are required for each possible location of the patterns. Because there are 10^4 possible locations with 100% overlap, 10^8 operations are required to perform a complete cross-correlation; scale and orientation compensations increase this number further. Parallel processing can reduce the time required to perform this very large number of operations but requires increased complexity and cost.

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A recent study (1) has been performed to establish the hardware requirements for using a digital correlation technique. It was concluded in this study that approximately 500 integrated circuits (IC) requiring 350 W of power are required to cross-correlate two 128 × 128 pixel pictures using 16-bit arithmetic precision. It was also assumed that eight reference maps would be carried in the processor. Six correlations could be performed on the 128 × 128 reference and 128 × 128 input scene in 0.5 sec. It was assumed that some parallel processing was used to obtain this speed.

Optical techniques can be used to perform cross-correlation and have the following advantages. An optical processor has an inherently large information capacity. A relatively modest optical system can handle scenes having over 10^7 resolution elements. Such a system handles two-dimensional data in a parallel and isotropic manner with a response time dictated by the time it takes light to travel the length of the processor, plus the time required for data input and output. An increase in the number of required resolution elements does not increase the response time or size of the optical system.

Optical data processing techniques can be divided into two general categories, incoherent and coherent. Incoherent optical processing operates on the intensity of the images to be correlated, that is, it handles only positive functions. Coherent processing makes use of the phase and amplitude of the images and can therefore handle complex functions. A study has been performed that compares the two optical processing techniques (2). This study demonstrated that typically a larger output signal-to-noise ratio and a greater precision can be obtained using coherent rather than incoherent processing.

Optical processing is only one of several analog techniques that can be used to perform correlation. A comparison of these analog techniques with digital processing has been made (3) and the results show that optical processors now out perform digital systems in speed and cost.

In all correlation systems, variations in the input scene when compared to the on-board reference scene can cause a reduction or loss of the correlation signal. The ability of a processor to handle variations in the input scene will determine if a particular correlation technique is successful. The most common scene deviations are scale, rotational orientation, intensity, aspect angle, and overlap. A typical processor can handle errors of ±5% in scale. Larger errors can be handled by using additional reference images or by change in magnification of the input image. Variation in rotational orientation can be reduced by providing attitude control to the missile. A typical

optical processor can handle ±2° rotational errors although this is a severe error for a digital system. Other compensation techniques for rotational variations include using additional reference images or rotating the input optically, electronically, or digitally. A change of intensity or shading can be a serious problem for a noncoherent processor or a digital processor that matches scenes in real space by an overlay process or by identification of key features. It is not a problem for those systems that first obtain the Fourier transform of the scene (such as a coherent processor) for they can bandpass filter the spatial frequencies of the scene before correlation. A small change in aspect angle is a distortion of the scene and can be handled by a nonuniform magnification change across the scene area. Large aspect angle changes require that additional reference scenes be stored on board. Overlap of the input scene beyond the boundary of the reference scene causes a reduction in the signal-to-noise ratio of the correlation. This problem can be handled by making the reference scene larger than the input scene.

It should be remembered when considering all of these errors that, because of energy requirements, the missile should not be designed to correct to a predetermined trajectory but should be designed to home on the target from a point on the actual trajectory.

In the design of optical processors very little attention is paid to the number of resolution elements in the input because this parameter does not affect the speed of the correlations. However, in the design of digital systems the reduction of this parameter is a major consideration. Thus, the digital and optical systems which have been designed are not equivalent devices and cannot be directly compared.

A sensor on board a missile will typically provide a low resolution scene for the terminal guidance system. A previous study (4) has demonstrated that the use of low resolution imagery reduces the sensitivity of the system to scale and rotation errors in the input scene while still providing an adequate correlation signal (signal-to-noise ratio greater than 15 dB). Additional advantages are also obtained by the use of low resolution imagery. The size of the optical elements required in the processor is reduced and the coherence requirements on the light source for the coherent optical processor are reduced, allowing laser diodes to be used.

In this paper, the design of a real time coherent optical processor will be described that will operate using realistic, low resolution input imagery. The design incorporates a bank of reference images

to provide the capacity for handling variations in aspect, rotation, and scale. This bank is scanned in time so that it can be determined which reference images are providing correlation signals.

THE EXPERIMENTAL SYSTEM

A coherent optical correlator operating at TV frame rates and utilizing a liquid crystal optical modulator was constructed for these experiments. Figure 1 shows a schematic of the system. Details of its operation are given in a previous report (5).

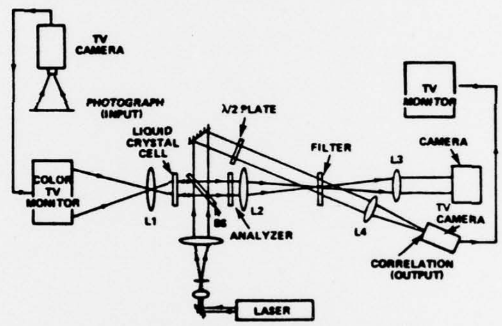


Figure 1. Schematic of coherent optical filter.

CROSS CORRELATION EXPERIMENTS

A series of experiments was performed using aerial photographs to demonstrate real time performance of the optical processor. Three classes of scenes were chosen which are representative of potential military targets. Photographs made in 1962 were used to record matched filters. These photographs were cross correlated with photographs of the same areas made in 1970. No attempt was made to optimize the filter parameters for each input image although a K-ratio was chosen to record spatial frequencies between approximately 0.5 and 4.0 ℓ/mm. This yielded good correlation signal-to-noise ratios for input images of urban and rural areas and structures such as airports and bridges.

Figure 2A is a photograph of a 1962 airport scene on the correlator input monitor. Figure 2B is the output from the liquid crystal modulator. The matched filter made from this input is shown in Figure 2C. The 0-50 scale corresponds to 1 mm. The matched filter was illuminated with the reference beam to reconstruct the image of Figure 2D. The features on which the filter will correlate are readily seen. The bandpass filtering property of the matched filter is apparent from the edge enhancement in the reconstructed image.

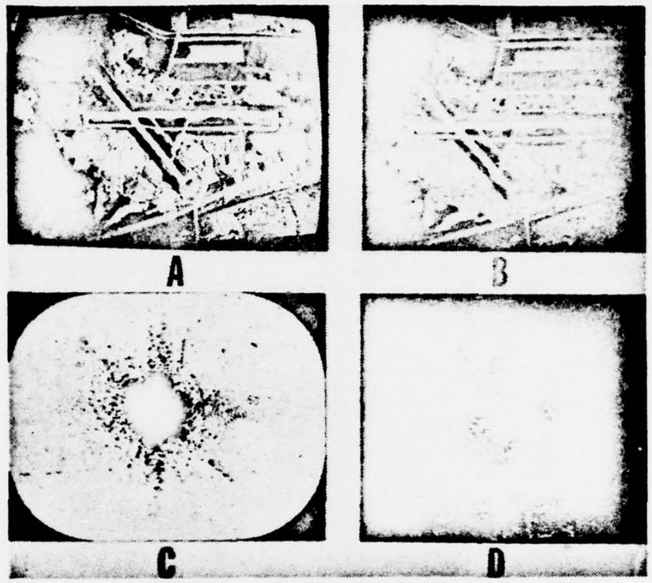


Figure 2. (A) TV image of airport in 1962, (B) modulator output; (C) matched filter made from this scene, and (D) image reconstructed from filter.

A 1970 aerial photograph of the same scene was correlated with the filter made from the 1962 photograph. Cross-correlation and tracking are demonstrated in Figure 3. Figure 3D is a triple exposure showing the correlation spot for each of the three positions of TV input image. The displacement from Figure 3A to Figure 3C corresponds to 680 m on the ground. An oscilloscope trace of a horizontal TV camera scan line through the center correlation spot is shown in Figure 3E. The noise in these traces is electronic noise from the TV camera. The halfwidth at half height for the correlation peak represents approximately 15-m displacement in the scene. Similar results were obtained for other classes of scenes.

EXPERIMENTS WITH RADAR IMAGERY

Tests were performed with imagery used in another terminal guidance program. The purpose of these experiments was to determine if the simulated radar imagery would correlate with actual radar imagery and to obtain performance data on which to base an improved correlator design. The simulated radar imagery is shown in Figure 4A as it appeared on the TV monitor input to the correlator. This photograph shows an area estimated to be 5.2 km in diameter. Figure 4B shows the image formed by the liquid crystal cell. A matched filter (Figure 4C)

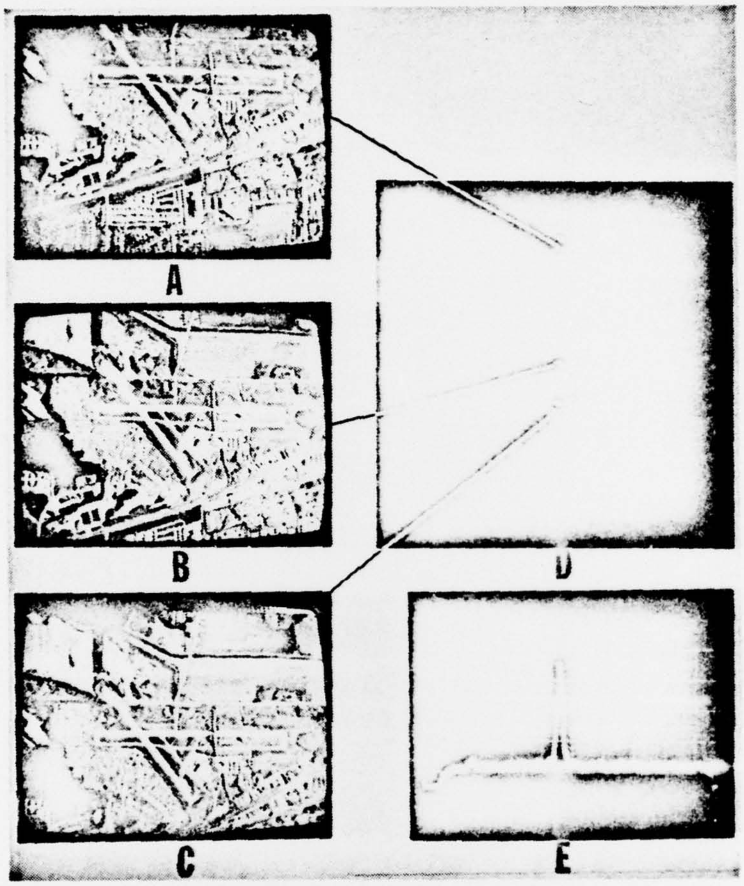


Figure 3. (A, B, C) positions of 1970 airport image corresponding to (D) peaks in correlation plane, (E) oscilloscope display of TV line scan through the central cross-correlation peak.

was constructed for this image with a spatial frequency bandpass of 0.2 to 0.8 ℓ/mm, chosen to match the frequency content of the radar imagery. The image reconstructed from the filter is shown in Figure 4C. Its low quality is due in part to problems of extraneous scattered light and low light level.

An actual radar image that was not grossly distorted relative to the simulated image could not be obtained. A scheduling problem prevented the recording of high quality images. The remaining tests were performed with the original simulated radar image and therefore were auto-correlations.

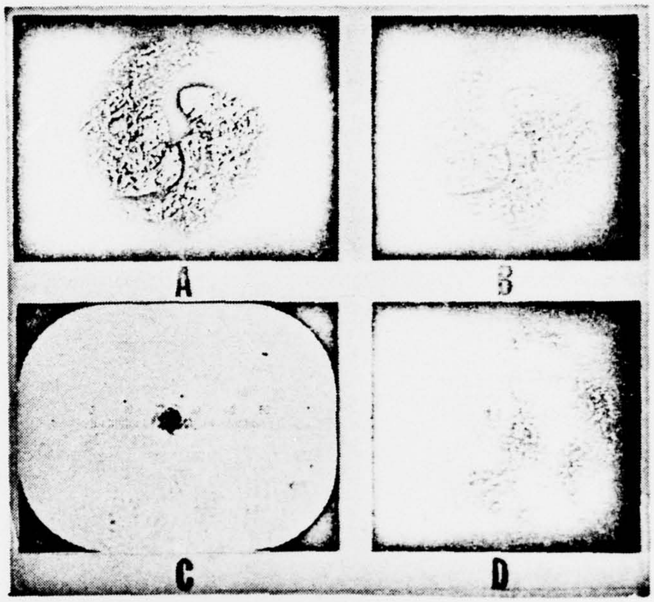


Figure 4. (A) TV display of simulated radar image, (B) modulator output image, (C) matched filter, and (D) image reconstructed from matched filter.

Figure 5A shows the correlation plane and Figure 5B is a trace through the center of the auto-correlation peak as detected by the TV camera at the output of the correlator. The correlation is distinct and well above noise level. The half-power width is 1/60 of the width of the input image. It should be possible to estimate the center of this peak to at least 1/5 of its width, thus giving an estimated accuracy of 1/300 or 0.3% of image width. The correlation peak was also detected and displayed with a photodiode array to confirm the feasibility of using this detector array in a compact breadboard system.

The required filter alignment and input scale and rotational alignment accuracies were determined by adjusting the system until 50% decrease in the height of the correlation peak was observed. The tolerances measured are ±12 μm for lateral filter position, ±2° for image or filter rotation and ±4.3% for image scale change.

A measurement was made of the light energy incident on the input image and the energy in the correlation peak. Energy input over the 12.5-mm diameter image was 1.5 mW and the energy in the correlation peak was 5×10^{-3} μW. No attempt was made to improve or optimize the system efficiency.

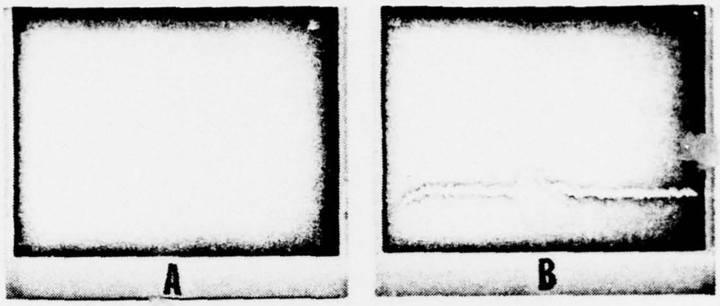


Figure 5. (A) correlation plane and (B) oscilloscope display of TV line scan through the simulated radar image autocorrelation peak.

In a tactical correlator it would probably be necessary to generate the filter on a separate optical system and load it into the correlator. A matched filter was recorded using one liquid crystal modulator and the correlation was performed in the same system using a different modulator. The correlation spot amplitude and signal-to-noise ratio were the same as those measured using one modulator to record the filter and to input the image to be correlated.

PROPOSED CORRELATOR CONFIGURATION AND PERFORMANCE ESTIMATES

A. Image and Filter Format

Correlator configurations are dependent upon the input image size and resolution. It will be assumed that this correlator is to operate on low resolution images with relatively few pixels. As the input data, the image will be assumed to consist of 128 × 128 or 1.64×10^4 pixels and the reference image from which the matched filter is made to consist of 256 × 256 or 6.55×10^4 pixels. Having the reference larger than the input insures that the correlation peak amplitude will not vary due to relative lateral displacement of the images.

For a reasonable balance between input image and its Fourier transform size, an input image format of 22 pixels/mm which gives an image size of 6 × 6 mm and a reference image twice as large will be chosen. If the Fourier transform lens has a 200-mm focal length and laser diodes are used as light sources with $\lambda = 820$ nm, the maximum diameter of the Fourier transform is 3.6 mm for data and 7.2 mm for sampling frequency. For a correlation peak displayed at a distance of 200 mm from the Fourier transform plane, the minimum size of the correlation spot should be approximately 200 μm. The location of this spot should be within an area 6 × 6 mm in size if the input image is to overlap the reference

completely. A detector having a resolution of 100 μm should be sufficient and the area covered need not exceed 6 × 6 mm. As a minimum, 100-μm detector resolution is needed to detect correlation peaks while 20-μm resolution would provide a much better estimate of the location of the correlation peak, to approximately 1/5 the width of the correlation peak.

Using a cathode ray tube (CRT) or an equivalent input device (Figure 1), scale search can be performed by changing the CRT deflection amplifier gain to change the image size. By changing the horizontal gain as a function of vertical position, small aspect angle changes or distortions can be searched.

B. Filter Multiplexing

Multiplexing can be performed by the use of several input image illuminating beams and numerous parallel filters at the Fourier transform plane. Figure 6 shows the basic arrangement. At the left are several light sources which can be turned on either one at a time or simultaneously. These sources might be laser diodes, for example. Light from each source passes through the input image and forms a Fourier transform that is separate from those of adjacent light sources. A different matched filter can be located at each transform location. The correlation from each source can be made to coincide at the output plane or appear at separate locations. If they coincide, then one detector can be used for all filters and the filters would be used in time sequence. If the correlations appear at separate locations at the output plane, then each correlation would have its own detector and the correlations could be performed simultaneously; the latter arrangement is faster but requires multiple detector arrays. All of the light from each source is used to perform correlations with one filter. To keep the complexity to a reasonable level, an array of up to 5 × 5 light sources for a total of 25 parallel processors could be used.

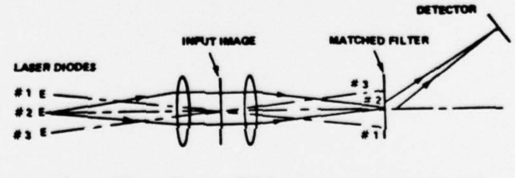


Figure 6. Matched filter multiplexing with multiple light sources.

Another method of multiplexing was described by Vander Lugt (8). Numerous filters are superimposed at the same location in the Fourier transform plane so that correlation peaks from each are located separately at the output. This arrangement requires multiple detectors in the output plane. The number of such superimpositions is limited by space available at the output plane and by the fact that light is equally divided between all correlations and thus decreases as $1/N$, where N is the number of superimposed filters. Vander Lugt demonstrated the use of nine superimposed filters which seems to be a realistic maximum number.

Using both multiplexing techniques simultaneously, a total of 9×25 or 225 different filters could be recorded at the Fourier transform plane. If the scale search for ten different image sizes for each of the 225 filters is included, this correlator could perform a total of 2250 different correlations. These 225 filters might include different images, angular orientations, or aspect angles.

C. Estimate of Correlation Time

An optical correlator takes a Fourier transform and performs correlations almost instantaneously. The readout of data is limited by the rate of scanning the output device and by the light energy used in the processor to charge light detector cells. The time to load the image into the processor is determined both by the scan rate of the sensor or sensor display and by the response time of the light modulator.

Output Detector - As an example, a commercial 100×100 element detector array with elements spaced on 60-μm centers and a 6×6 mm active area will be considered. The usable range of sensitivity extends from a minimum of 0.16 ergs/cm^2 to a saturation exposure of 8 ergs/cm^2. The maximum scan rate of 10 MHz permits one complete output plane scan in 1 msec. The power consumption for a detector array and its associated electronics is approximately 10 W.

Light Sources - A 10-mW laser diode with output at 820 nm and having 4 nm spectral bandwidth can be used in the correlator. A typical diode has an emitter area of 2×13 μm and an overall package diameter of 10 mm. Input power is less than 1 W. Its switching time is less than 1 nsec and therefore can be considered instantaneous. Its wavelength matches the peak response of the detector array. It is estimated that approximately 10% of its output energy will enter the correlator.

Correlator Input Devices - Several types of input devices using liquid crystal or photoconductor-thermoplastic materials could be employed in an optical correlator. Because previously described experiments were performed with the Hughes Aircraft noncoherent-to-coherent image converter and complete specifications are available, the computational estimates used here will be based on this device using a CRT as the source of the image and a lens to image the CRT picture onto the image converter.

Correlation Time - In generation of the input image, it will be assumed that the image data are collected and stored in a digital memory and read onto a CRT which is imaged onto the liquid crystal cell. Thus for a 128×128 point array there are 1.6×10^4 points. These can be scanned at a 1.6-MHz rate so that the image is read onto the CRT in 10 msec. Because the image converter response time is 15 msec and turn-off time is 25 msec, it will be assumed that a usable image exists during a 10-msec period from 20 to 30 msec after the start of the scan, and that an additional 20 msec are needed for a complete image turn-off. During these 10 msec, five sequential sets of correlations, each with nine parallel correlations, can be performed for a total of 45 correlations. Thus, in 50 msec, 45 correlations can be performed at an average rate of 900 correlations/sec.

The data arrangement for the correlator would depend upon factors such as the angular search or scale search required, the storage of multiple targets, and the total operating time for the correlator. Table 1 summarizes the performance capability of the correlator for a few examples of input and filter combinations.

TABLE 1. SUMMARY OF SPECIFICATIONS FOR PROPOSED OPTICAL CORRELATOR

Reference data format (filters)	256×256 points
Input image format (real time)	128×128 points
Total number of reference filters	225
Maximum number of scale changes	10
Filter format	25 sets of filters in time sequence, nine filters per set at a time
Correlation time	2 msec per set
Image enter and erase time	50 msec (includes 10 msec computation time)
Correlator power consumption	<2 W
Correlator size	1500 cm^3 (100 $in.^3$ or 0.05 ft^3)
Correlator weight	5 kg (12 lb)

Computational Capability per Half-Second Period for Various Data Arrangements

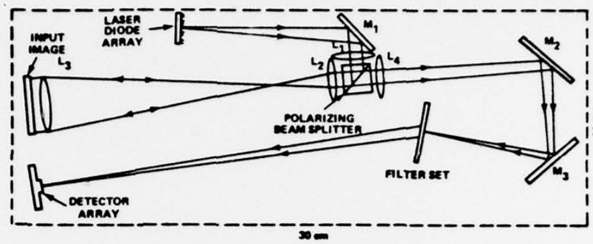
New Images	Scale Increments per Image	Filters Accessed	Correlations
1	1	225	225
1	10	45	450
1	10	9	90
2	5	45	450
5	1	90	450

Since the laser diodes require 1 W of power and the liquid crystal input device and detector array a fraction of a watt, the total power consumption should be less than 2 W. This does not include the power requirements of the CRT and computer components expected to be used with the correlator. The charge-couple-device (CCD) addressed liquid crystal modulator under development by Hughes could be used directly in place of the incoherent-to-coherent image converter (9). With the latter arrangement, the computer could be packaged into 1500-cm^3 (0.05-ft^3) volume and would probably weigh less than 5 kg (11 lb).

A BRASSBOARD CORRELATOR

Figure 7 shows a proposed design for a correlator to demonstrate the concepts discussed in the previous section. Current state-of-the-art components are used. While the general arrangement is the same as that discussed in the previous sections, this correlator has four superimposed filters instead of nine. This change was considered necessary to reduce complexity and to increase light level in each correlation peak. The image input device is a Hughes Aircraft liquid crystal TV display having 4 pixel/mm resolution. This low resolution makes the input light modulator approximately 33 × 33 mm in size and gives a very small Fourier transform. To increase its size, the Fourier transform is magnified by lenses L_2 and L_4 by the ratio of f_4/f_2, where f is the lens focal length. This provides a Fourier transform focal length of 200 mm. The use of the combination L_2, L_3 allows for the use of a small polarizing beamsplitter and reduces the overall correlator size. The lens combination L_2 and L_3 also reduces the image size to 6 × 6 mm to the right of lens L_2. The preceding lens focal lengths were chosen primarily to achieve a convenient scale and do not represent the minimum possible (10).

The matched filter consists of an array of 5 × 5 filters each occupying 7.2 × 7.2 mm of space. At each filter location, four different filters are superimposed. The correlation peaks from each fall on a detector array such as a Reticon RA 100 × 100 which has a spectral sensitivity matching the laser diode output. One-fourth of this detector could be allocated for each filter giving 50 × 50 elements for each correlation. For the parameters shown in Figure 8, the width of the correlation peak can be expected to be approximately 100 μm while the detector elements are on 60-μm centers. This allows for some improvement in estimating the location of the peak.



LENSES	FOCAL LENGTH (mm)	DIAMETER (mm)
L_1	100	10
L_2	25	12.5
L_3	125	50
L_4	200	10

Figure 7. Brassboard optical correlator.

The light sources are laser diodes such as RCA Type C30127. Of the 10-mW output, approximately 10% can be utilized and should give sufficient light output at the detector array.

The matched filter array would be constructed on an optical system separate from the correlator. The filters could either be recorded on a high resolution photographic emulsion, on dielectric materials such as dichromated gelatin for higher efficiency, or on thermoplastic photoconductive recording materials. The latter would be most suitable for operational systems because it is nearly real time and the recording is permanent until erased.

SUMMARY AND CONCLUSIONS

Coherent optical correlators are well known to give distinct autocorrelation and cross-correlation peaks between data having precise scale, orientation, and contrast match. These peaks are generally quite narrow and have a low background level because correlations are performed on the high-frequency content of the input image, such as edges and other details. Correlation time is independent of the number of data points on the reference filter and the input image, although in practice the time required to obtain a correlation is determined by the data read-in time and the correlation read-out time.

Experiments were performed with an existing optical correlator to determine typical correlator operating parameters. Special emphasis was placed on correlation of low resolution images because these would be typical for terminal guidance situations. Distinct correlations were obtained with simulated radar images and data on alignment accuracy of the optical system were obtained. Additional data have been compiled in a separate report (5).

An optical correlator suitable for guidance applications was designed and its correlation time estimated. The reference filter was assumed to contain 256 $\times$ 256 pixels; the input data had 128 $\times$ 128 pixels. It was estimated that 50 msec is required to complete one read-in and erase cycle and that during this time, up to five sequential correlations and up to nine parallel correlations can be performed and read out. The filter library could store up to 225 different reference functions; in addition, scale can be changed by rewriting input data on the input light modulator.

This proposed optical correlator would have very low power demands. The power consumption of the optical correlator itself, including laser diode light sources and photodiode detector arrays, would be less than 2 W. Additional power would also be required for electronic circuitry to handle data input and output and to control the operation of the correlator.

The optical correlator can be packaged into 1500 cm^3 (0.05 ft^3) of space and is expected to weigh less than 5 kg (12 lb). Additional size and weight reductions could be achieved by miniaturization of components and the use of holographic optical components in place of lenses.

A brassboard correlator was designed with presently available components. This correlator can be made small and lightweight, with a capability of storing up to 100 reference filters. A variety of tests could be performed with this correlator to demonstrate the feasibility of compact coherent optical correlators.

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